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Abstract

To assess the influence of clothing on dermal uptake of SVOCs, we measured uptake of selected airborne phthalates for an individual wearing clean clothes or air-exposed clothes and compared these results with dermal uptake for bare-skinned individuals under otherwise identical experimental conditions. Using a breathing hood to isolate dermal from inhalation uptake, we measured urinary metabolites of diethylphthalate (DEP) and di-n-butylphthalate (DnBP) from an individual exposed to known concentrations of these compounds for 6 hours in an experimental chamber. The individual wore either clean (fresh) cotton clothes or cotton clothes that had been exposed to the same chamber air concentrations for 9 days. For a 6-hour exposure, the net amounts of DEP and DnBP absorbed when wearing fresh clothes were respectively 0.017 and 0.007 μg/kg/(μg/m^3) ; for exposed clothes the results were 0.178 and 0.261 μg/kg/(μg/m^3) (values normalized by air concentration and body mass). When compared against the average results for bare-skinned participants, clean clothes were protective, while exposed clothes increased dermal uptake for DEP and DnBP by factors of 3.3 and 6.5 respectively. Even for non-occupational environments, wearing clothing that has adsorbed/absorbed indoor air pollutants can increase dermal uptake of SVOCs by substantial amounts relative to bare skin.

Introduction

Dermal absorption of organic compounds directly from air has been observed for some volatile and semi-volatile compounds. In reviews by Rehal et al.[1] and Rauma et al.[2] a handful of volatile organic compounds (VOCs) have been observed to have dermal uptakes

that are substantial compared to inhalation intakes. For example, Piotrowski[3,4] found that nitrobenzene and phenol doses via dermal absorption were about 50% those due to absorption by inhalation. Weschler and Nazaroff [5,6] argued that the dermal absorption dose from air could also compare with or exceed the dose due to inhalation for semi-volatile organic compounds (SVOCs) that meet specific criteria under steady-state conditions. In a refinement of that model for non-steady-state conditions, Gong et al.[7] showed that timing of exposure can significantly influence dose due to resistance and accumulation within the dermis. In a test of the hypothesis that the dermal dose of SVOCs from air could be significant, Weschler et al.[8] showed that dermal absorption was approximately equal to inhalation dose for six bare-skinned male participants exposed to diethylphthalate (DEP) and di n-butylphthalate (DnBP) for six hours in a chamber.

A few studies have evaluated how clothing may influence dermal uptake of organic compounds from air or by transfer from treated fabrics. Piotrowski[3] found that clothing reduced dermal uptake of airborne nitrobenzene by about 20-30% but had no observable effect on phenol absorption.[4] Organics that have been applied to clothing can be also absorbed. Blum et al.[9] observed metabolites of a flame retardant in the urine of children who had worn clothing treated with this flame retardant. Similarly, subjects wearing permethrin-impregnated battle dress uniforms absorbed this insecticide as evidenced by urinary metabolites[10–12].

We hypothesize that sorption to clothing acts either to reduce or to increase dermal uptake, depending on the extent to which the clothing has equilibrated with room air

contaminants prior to wearing. For some compounds, the boundary layer of air adjacent to the skin presents greater resistance to transport than does the stratum corneum and viable epidermis.[6] For such compounds uptake is sensitive to the magnitude of the boundary layer permeability[7] and could be altered significantly by sorption to fabrics, especially for compounds with high air-fabric partition coefficients.

For fabrics that are initially clean, adsorption to fabric fibers should decrease fabric permeability, and lower overall dermal uptake, by reducing diffusional flux through the fabric. With continued exposure, fabric permeability would increase as fabric surfaces equilibrate with SVOCs. Fabrics that are exposed to building air for extended periods (e.g. hanging up in a closet) may absorb a substantial quantity of SVOCs, or even reach equilibrium, prior to wearing. For these clothes, we predict that dermal uptake will be higher than uptake to bare skin.

Our objective is to test this hypothesis with two compounds that have been predicted, and recently shown, to exhibit low dermal uptake resistance relative to mass-transfer resistance through the layer of air adjacent to body surfaces. In this study, we measure urinary concentrations and total excretion of DEP and DnBP metabolites during and after a participant is exposed for 6 hours to known air concentrations of DEP and DnBP for 2 conditions: i) wearing freshly cleaned cotton clothing; ii) wearing previously clean cotton clothing that had been exposed to the phthalates for at least one week. Inhalation uptake is controlled with a breathing hood. Results are compared against results from six individuals

who wore only shorts but were subjected to nearly identical conditions (results reported in Weschler et al.[8]).

Methods

The experiments reported here were integrated into the dermal uptake experiments reported by Weschler et al.[8] and nearly all procedures, conditions and analytical methods are therefore identical. The clothed individual was exposed to phthalates in the same chamber at the same time as bare-skinned participants during two of the chamber exposure intervals, specifically Wednesday of the 1st week and Tuesday of the 2nd week.

Exposure chamber

The 55 m^3 chamber housed two mixing fans, desks and chairs. The air exchange rate was maintained at 0.7 1/h and the temperature was controlled at 30°C. The relative humidity was not controlled and ranged from 20 to 35% during the experiments. A breathing hood (Amron International, Vista, CA, #8890 Oxygen Treatment Hood) was used so that the participant in the clothing experiments could breathe clean air from outside the chamber, thus allowing for the separation of dermal from inhalation dose. See Figure S.1 for an image of the participant wearing test clothing and the hood while seated in the experimental chamber. Air concentrations of DEP and DnBP were maintained by continuous emission from aluminum panels (total area of 12 m^2) coated with Latex paint. The paint had been formulated with 1% DEP and 10% DnBP (by weight), and was used to deliver these phthalates into chamber air at a relatively constant emission rate.[8,13]

Clothing and clothing preparation

Clothing was purchased from two different clothing stores in Rolla, Missouri, USA. Each set included a cotton undershirt, a pair of cotton jeans, a long-sleeved cotton tee shirt, cotton underwear and cotton socks. Details such as size, style and manufacturer can be found in Table S.1.

Two sets of clothing were prepared by washing all pieces at the same time in a standard clothes washer using unscented detergent. They were then dried in an electric dryer on the "medium" setting and each set was packaged separately in two layers of clean aluminum foil until use. During the first 6-hour exposure period, one set was worn directly from its package and is denoted "fresh". Another set of clothing was exposed to chamber air for 9 days and denoted as "exposed". This exposure took place in the same chamber, under the same conditions and at the same time as bare-skin dermal uptake experiments occurred; the latter are described in Weschler et al.[8] The clothing was hung inside-out in the path of fans to improve transfer of phthalates from air to the clothing. The air concentration was measured during days 2 and 3 of the 9 day clothing-exposure interval. During these periods, the average concentrations for DEP were 250 and 233 μg/m^3 and that of DnBP was 123 and 114 μg/m^3.

Preparation of participant

Because there were a limited number of breathing hoods available in the exposure chamber, it was only possible to study one clothed participant. The participant was a 48 year old Caucasian male, 192 cm tall weighing 91 kg. The participant followed the same

restricted diet and restricted use of personal care products protocol described in Weschler et al.[8] These restrictions were intended to reduce background metabolites of DEP and DnBP in the participants' urine. In brief, for 12 hours prior to exposure and 54 hours after exposure began, the participant only ate Swedish dried bread and ate thick-rinded fruit such as oranges, bananas and melons. He drank only tap water or tea made from tap water. The participant showered without soaps or detergents 24 hours prior to the experiment and showered without soaps again 48 hours after the beginning of an exposure. The research protocol was approved by the Capital Region of Denmark Committee for Research Ethics. The participant provided informed consent before participation and consented to publication of his photo.

Description of exposure periods

The participant participated in two exposure experiments. The first took place on a Wednesday coincident with the 2nd set of exposure experiments during the first week described in Weschler et al.[8] The participant collected two urine samples on the morning of the experiment. Immediately before entering the chamber the participant collected a urine sample, changed into the "fresh" set of experimental clothes, donned a breathing hood and entered the chamber at 11:00. The participant sat at a desk for most of the 6-hour exposure period and left the chamber once briefly to collect a urine sample. At 17:00, the participant left the chamber and changed into his normal clothing. Following this, the participant maintained the restricted diet and personal product restrictions and collected all urine for 48 hours. The second exposure experiment took place on a Tuesday coincident with the 3rd set of exposure experiments during the second week described in Weschler et al.[8] The

procedure was identical to the first experiment except that the participant changed into the "exposed" set of clothes before entering the chamber at 10:00 (leaving at 16:00).

Analysis of air and urine

Air concentrations of phthalates were determined by first collecting 6 L samples of air with Tenax-TA filled thermal desorption tubes, and analyzing by thermal desorption followed by gas chromatography using a mass selective detector. Phthalates were quantified using original standards. The concentrations in air and other conditions are tabulated in Weschler et al.[8]

Urine samples were weighed on the day of collection and stored in a freezer until they were shipped overnight to the Institute for Prevention and Occupational Medicine of the German Social Accident Insurance in Bochum, Germany. Urine samples were analyzed for mono-ethyl phthalate (MEP), a metabolite of DEP, as well as mono-n-butyl phthalate (MnBP) and 3OH-mono-n-butyl phthalate (3OH-MnBP), metabolites of DnBP. The concentrations of these metabolites were determined by two-dimensional high performance liquid chromatography coupled to tandem mass spectrometry (LC/LC–MS/MS) using internal isotope-labeled standards after enzymatic deconjugation of the phthalate metabolites from the glucuronidated form following methods published by Koch et al.[14,15] Other details of analytical methods can be found in Weschler et al.[8]

Calculations

Calculated total uptake of DEP or DnBP during the 6 hour exposure period was based on methods described by Koch et al.[15–17] and outlined in Weschler et al. [8] Metabolite concentrations were converted to mass excreted and then converted to parent molecule uptake using predetermined metabolic conversion factors. In the "fresh clothes" experiment there was very low overall dermal uptake of DEP and DnBP (see Results and Discussion). To better quantify uncertainty in this case, background uptake has been determined in a somewhat different manner than in Weschler et al.[8] For the present participant, little residual uptake from the 6-hour experiment remained, relative to background uptake, for the last four urinations of the fresh clothes experiment (collected from 40.5 to 50.0 hours after exiting the chamber). Therefore, the average dose rate (total dose/elapsed time) from these samples was subtracted from the dose rate calculated for each post-exposure sample for both fresh and exposed clothes experiments. This was multiplied by the sample time interval, and the result from each interval summed, to determine the background-corrected total dose. Dermal uptake was also corrected for DEP and DnBP measured in the breathing hood air (40.7 μg/m^3 and 5.7 μg/m^3, respectively) using a breathing rate of 0.7 m^3/h. Dermal uptake was then normalized by the air concentration during the 6 hours in the chamber and the participant's weight. Also reported is the average flux for the 6-h exposure, corrected for background uptake and hood air inhalation. Exposed surface area is taken as 2.06 m^2, estimated by equation 7A-7 of the Exposure Factors Handbook[18] and corrected for the area of the head (6.6% of total). To compare the rate of uptake among exposure conditions and between phthalates, we calculated a normalized metabolite excretion rate. First we calculated the slope of net metabolite vs time from initial sample (after exposure begins) to the last sample that

includes no more than 75% of total net metabolite excreted. This slope divided by the total mass excreted was defined as the normalized metabolite excretion rate. See Table S.2 for additional details regarding the calculation methods.

Results and Discussion

Major quantitative results are shown in Table 1. There is a striking difference between results for fresh and exposed clothing experiments. The net metabolites excreted over the 54 hour period after initiation of exposure are far higher for exposed clothes than for fresh clothes, indicating that parent compound uptake is much higher for exposed than for fresh clothes When corrected for background uptake rate and inhalation from the breathing hood and normalized by body mass and air concentration, wearing exposed clothes resulted in DEP and DnBP uptakes that were 11 and 36 times greater, respectively, than when wearing fresh clothes. The mass of metabolites excreted over the first 24 hours by the volunteer wearing exposed clothes (3.6 mg MEP; 2.1 mg MnBP) approaches that due to application of a 2% DEP/DnBP cream over most of the skin of subjects as reported by Janjua et al.[19] (MEP range 2.5-85 mg; MnBP range 3.6-18 mg).

The ratio of the normalized uptake of DEP/DnBP was very different for the two scenarios. For exposed clothing, normalized uptake of DEP is somewhat smaller than for DnBP (DEP/DnBP = 0.7), but for fresh clothing it is much higher (DEP/DnBP = 2.3). This suggests that fresh clothes retard uptake of DnBP more than DEP and/or that exposed clothes enhance uptake of DnBP relative to DEP. Both mechanisms are consistent with a higher cloth/air partition coefficient for DnBP, which has a higher molecular weight than DEP.

Normalized dermal uptake for both fresh and exposed clothes differ substantially from uptake to bare skin as described in Weschler et al.[8] For comparison, results for bare skin and clothing experiments are shown in Figure 1. For exposed clothes, normalized uptake of DEP and DnBP are 3.3 and 6.5 times greater, respectively, than the average of bare skin results and 1.9 and 3.9 times higher than the highest uptake observed in the bare skin experiments. For fresh clothes, uptake is 3.2 and 5.6 times lower than the average for bare skin experiments. Based on a t-test, the probability, *p*, of the results stemming from random variation was $<10^{-4}$ for exposed clothes and < 0.017 for fresh clothes. These findings are consistent with the hypothesis that fresh clothes retard uptake and exposed clothes increase uptake compared with bare skin.

A comparison of the results, accounting for participant age, is also enlightening. Weschler et al.[8] observed a striking relationship between dermal uptake and age. Shown in Figure 2a and 2b are plots of net amounts of MEP and MnBP excreted, from the time exposure began until the end of urine sampling, for the two clothing experiments (worn by a 48 year-old participant) and bare skin results from the 47 year-old participant reported by Weschler et al.[8] For both phthalates, wearing exposed clothing increased the excretion rate and net excretion by a large margin. Wearing fresh clothes significantly reduced excretion rate and net excretion.

In Figure 3, normalized clothing results for uptake of parent compounds are plotted against age along with the normalized results for all six bare-skinned participants. The clothing

results are clearly "off the line"; the exposed clothes result in much higher uptake and fresh clothes much lower uptake than for bare skin. Again, using the 47 year-old participant from Weschler et al.[8] as the best comparator, we observe that exposed clothes resulted in 2.3 and 3.4 times more uptake of DEP and DnBP respectively. Fresh clothes resulted in 4.5 and 11 times lower uptake.

The excretion rate of metabolites differs among conditions and between phthalate metabolites. The difference between MnBP and MEP is apparent for exposed clothes in Figure 2, with MEP rising faster than MnBP. The normalized excretion rate for both conditions studied in this research and for the six bare skin participants is shown in Figure 4. To make the comparison more clear, the bare skin results for participants wearing hoods are grouped with the clothed results. Qualitatively, clothed results are similar to bare skin results: the normalized excretion rate of MEP is higher than for MnBP. For both MEP and MnBP, the excretion rate is higher for exposed clothes than for fresh clothes. This is consistent with the hypothesis that fresh clothes act as a barrier and delay transport from air to skin. The difference is more pronounced for MnBP than for MEP, possibly due to stronger sorption of DnBP to clothing.

The results support the hypotheses that 1) fresh clothes are protective, reducing uptake of DEP and DnBP compared with bare-skinned participants and 2) exposed clothes increase uptake. Although only one participant was tested (in two exposure periods), we believe the results are compelling, especially when compared with the narrow range of results for six bare-skinned participants. All results are significantly different from the six bare-skinned

participant results. When compared by age, the difference is even more apparent (Figure 3). However, replication of these results with a larger number of participants will be valuable.

For both DEP and DnBP, the dose while wearing fresh clothes is small and could have come from a combination of penetration through clothing and absorption by bare skin. The participant in this study was not completely clothed: the hands were bare. We can estimate the absorbed dose by hands assuming that hands are 4.7% of an average adult male's total surface area.[18] We will use participant 2, the bare skinned participant closest in age to the clothed participant, for comparison and will assume that the shorts worn by participant 2 covered approximately 5% of his total surface area. Correcting for the reduced total exposed area due to hood (3.9% of total surface area) and shorts, the normalized dermal uptake due to exposed hands for participant 2 would be approximately 0.004 and 0.003 μg/kg /(μg/m^3) for DEP and DnBP respectively. These values can be compared with 0.017 and 0.007 μg/kg /(μg/m^3) for DEP and DnBP for the fresh clothes experiment. Hence, for DnBP, uptake by bare hands could represent a substantial fraction of total uptake from the fresh clothing experiment. It is also interesting to note that the estimated DEP uptake by bare hands accounts for only 25% of the observed uptake; therefore, penetration through clothing may account for much of the uptake.

It is perhaps intuitive that fresh clothes should impede transfer from air to skin of airborne contaminants. Clothing has been designed to protect workers from pesticide spray and industrial toxic gases. A recent paper reported on the ability of "every-day" clothing[20] to

reduce in vitro dermal penetration of chlorpyrifos from solution. But early human subject studies of VOCs showed little influence of clothing on dermal absorption of nitrobenzene and phenol.[3,4] This could be because sorption to cloth is weak for these low molecular weight compounds. Higher molecular weight, low volatility organic compounds are known to exhibit substantial air-fabric partitioning.[21,22] As volatility decreases, partitioning from air to fabric increases and we would anticipate that retardation of transport across fabric would also increase. Indeed, in this research we observed a lower normalized uptake of DnBP relative to DEP, consistent with the roughly 25 times lower vapor pressure of DnBP.

Given the complicated geometry of fabric and skin, and the potential for air movement through and under fabric, the data cannot be used to test more detailed models, to generate exposure estimates or to identify compound/fabric combinations that would be most protective or hazardous. Qualitatively, the transport of SVOCs into and out of clothing may be described well by a model of transport of contaminants through porous media.[23] In the context of this model, both advection and diffusion of contaminants through fabric would be retarded by sorption. Key parameters influencing transport and dermal uptake are likely to include the geometry and permeability of the fabric, how closely clothing fits, the air-to-cloth partition coefficient, the dermal permeability of the contaminant, the elapsed time the cloth is exposed to contaminated air after washing and the elapsed time clothing is worn.

Geometry and permeability of fabric. Transport of air and moisture through fabric has been extensively measured and modeled.[24–27] Hydraulic permeability lumps geometric

complexity of fabric into a parameter that characterizes fabric resistance to advective flux; hydraulic permeability is defined as the volume flux of air due to a specific pressure difference across the fabric in units of $cm^3/(cm^2\ s)$ (usually at a pressure difference equal to 125 Pa). Hydraulic permeability can range over several orders of magnitude: very low ($<0.1\ cm^3/(cm^2\ s)$) for dense or sealed materials and very high for loosely woven thin fabrics ($>300\ cm^3/(cm^2\ s)$). SVOC transport is likely to be more influenced by advection in loosely woven materials with a high hydraulic permeability; for tightly woven materials, diffusive transport is expected to dominate. For intermediate materials, the relative contributions of diffusion and advection will be influenced by pressure gradients, wind and movement.

How close clothing fits. Some sorbed SVOCs may transfer from cloth to skin by contact. However, since most of the surface area available for adsorption in a woven fabric is internal, only a small fraction of the sorbed SVOC is likely a consequence of transfer by direct contact with the outer fabric fibers. Instead, we believe that the more important mechanism is desorption from fiber surfaces and diffusion across a thin air gap to skin. For diffusion across a quiescent air gap, flux is proportional to the reciprocal of the air gap distance. The air gap distance was not measured in this study but we estimate it ranged from <0.1 cm to 0.5 cm. By comparison, a typical bare-skin concentration boundary layer is about 0.2 to 0.4 cm, which can be estimated by dividing the gas diffusivity of the SVOC ($0.056\ cm^2/s$)[28] by an air-to-skin deposition velocity (0.14-0.28 cm/s)[29]. Therefore, the initial flux from fabric to skin could be smaller, or more than 4 times greater, than from bulk air when wearing equilibrated clothing. Notably, this estimate overlaps the observed

ratio of uptake for exposed clothing to the average for bare skin (3.3 for DEP and 6.5 for DnBP).

Air-to-cloth partitioning. The sorptive capacity of fabric will influence how it reduces or enhances transport from air to skin. There is recognition that adsorption and desorption of indoor-relevant gases on fabrics for tobacco smoke products[30–32] and pesticides[21]can influence exposure. Several studies have shown that dry-cleaning solvents[33–36] and moth repellants[37] can sorb to clothing and subsequently desorb, increasing indoor concentrations. Specialty fabrics have been developed that sorb or react with chemical warfare agents or pesticides to protect the wearer.[38] However, we have only identified two papers[22,39] that report equilibrium partition coefficients for an indoor air contaminant and commonly worn fabrics. In one paper[22] the investigators measured equilibrium partition coefficients for airborne free-base methamphetamine and fabrics including cotton and polyester. The partition coefficients were high enough that mouthing of these fabrics was predicted to be the primary route of exposure for toddlers, similar to the observation by Gurunathan et al.[21] for chlorpyrifos and plush toys.

Dermal permeability. We anticipate that the compounds that are most likely to exhibit enhanced dermal uptake from exposed clothes are those that have high dermal permeability coupled with gas-to-fabric partition coefficients in an intermediate range (not too high, not too low). Uptake of compounds with low dermal permeability is limited by resistance across skin; modest changes in mass-transfer conditions external to skin will likely have little impact on overall uptake. Dermal permeability of compounds typical of

indoor air have been estimated by Weschler and Nazaroff.[6] They identified more than 30 common indoor pollutants that are predicted to have high dermal uptake relative to inhalation uptake. If a compound has too high a gas-to-fabric partition coefficient, this will retard transfer from the fabric to skin. On the other hand, if a compound has too small a gas-to-fabric partition coefficient, then exposed clothes have sorbed very little of the compound and there will be concomitantly little enhancement. It is in the intermediate range of gas-fabric partitioning that sorption to clothes prior to wear will have the greatest enhancement on uptake.

Elapsed time clothing sorbs contaminants and time clothing is worn. It takes time for fabric to adsorb airborne contaminants and approach equilibrium with gas phase concentrations. It also takes time for contaminants to desorb and transfer to skin. As an example, consider a tight-fitting shirt that has been washed, stored in the presence of a contaminant (in air) and then worn. If we assume that the characteristic time for the fabric to equilibrate (τ_e) is independent of the air concentration, then we can qualitatively compare this time to the actual time stored in the presence of a contaminant (t_s) or the time clothing is worn after storage (t_w). *Scenario 1:* $t_s < \tau_e$. For this scenario, the fabric has not equilibrated with the contaminant concentration in the air and may in fact continue to sorb contaminants even while worn. Regardless of the chemical, enhanced flux from cloth to skin will be limited. *Scenario 2:* $t_s \geq \tau_e$ *and* $t_w < \tau_e$. For this scenario the fabric is well equilibrated with a contaminant before wearing, but the time worn is short relative to the time it takes for the contaminant to reach a new steady-state. During the time worn, flux to skin will be enhanced but the mass adsorbed to fabric will not change substantially. This

scenario could be represented by a shirt worn for a short time that had adsorbed a relatively more volatile, low partition coefficient chemical; it could also be represented by a shirt worn for a longer period of time that had adsorbed a less volatile, higher partition coefficient chemical. *Scenario 3:* $t_s \geq \tau_e$ *and* $t_w > \tau_e$. Here, the shirt has been worn long enough that a substantial fraction of the contaminant has desorbed. While the initial flux to skin may be high, the time-averaged flux will be lower than for *Scenario 2* (all else being equal).

Since DnBP is anticipated to have a higher partition coefficient than DEP, we would anticipate that τ_e would be greater for DnBP than DEP. We observe a normalized dermal uptake that is higher for DnBP than DEP from exposed clothes. If the 6-hour period that the participant wears the exposed clothing is similar or longer than τ_e for DEP, then it may fall under *Scenario 3*, while DnBP falls under *Scenario 2*.

Conclusions

Clothing acts as a barrier to exposure, but also as a reservoir for recently adsorbed chemicals; the latter can increase dermal uptake. Not only are people subjected to airborne SVOCs while at home, they are also exposed to "home pollutants" outside of their residence when they wear clothing that has been stored in the presence of various SVOCs at home. Given the very large increase in the normalized dermal uptake of DEP and DnBP observed for exposed fabric in this study, we believe clothing-mediated dermal uptake is an under-recognized exposure pathway that could be a substantial or even a dominant exposure route for many chemicals. This is of potential importance in occupational as well as non-occupational settings.

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References

1 Rehal B, Maibach H. Percutaneous absorption of vapors in human skin. *Cutan Ocul Toxicol* 2011; **30**: 87–91.

2 Rauma M, Boman A, Johanson G. Predicting the absorption of chemical vapours. *Adv Drug Deliv Rev* 2013; **65**: 306–314.

3 Piotrowski J. Further investigations on the evaluation of exposure to nitrobenzene. *Br J Ind Med* 1967; **24**: 60–65.

4 Piotrowski J. Evaluation of exposure to phenol: absorption of phenol vapour in the lungs and through the skin and excretion of phenol in urine. *Br J Ind Med* 1971; **28**: 172–178.

5 Weschler CJ, Nazaroff WW. SVOC exposure indoors: Fresh look at dermal pathways. *Indoor Air* 2012; **22**: 356–377.

6 Weschler CJ, Nazaroff WW. Dermal uptake of organic vapors commonly found in indoor air. *Environ Sci Technol* 2014; **48**: 1230–1237.

7 Gong M, Zhang Y, Weschler CJ. Predicting dermal absorption of gas-phase chemicals: Transient model development, evaluation, and application. *Indoor Air* 2014; **24**: 292–306.

8 Weschler CJ, Beko G, Koch HM, Salthammer T, Schripp T, Toftum J *et al.* Transdermal uptake of diethyl- and di(n-butyl) phthalate directly from air: experimental verification. *Environ Health Perspect* 2015; doi:10.1289/ehp.1409151.

9 Blum A, Gold MD, Ames BN, Jones FR, Hett EA, Dougherty RC *et al.* Children absorb tris-BP flame retardant from sleepwear: urine contains the mutagenic metabolite, 2,3-dibromopropanol. *Science* 1978; **201**: 1020–1023.

10 Appel KE, Gundert-Remy U, Fischer H, Faulde M, Mross KG, Letzel S *et al.* Risk assessment of Bundeswehr (German Federal Armed Forces) permethrin-impregnated battle dress uniforms (BDU). *Int J Hyg Environ Health* 2008; **211**: 88–104.

11 Rossbach B, Appel KE, Mross KG, Letzel S. Uptake of permethrin from impregnated clothing. *Toxicol Lett* 2010; **192**: 50–55.

12 Kegel P, Letzel S, Rossbach B. Biomonitoring in wearers of permethrin impregnated battle dress uniforms in Afghanistan and Germany. *Occup Environ Med* 2014; **71**: 112–117.

13 Schripp T, Salthammer T, Fauck C, Beko¨ G, Weschler CJ. Latex paint as a delivery vehicle for diethylphthalate and di-n-butylphthalate: Predictable boundary layer concentrations and emission rates. *Sci Total Environ* 2014; **494**: 299–305.

14 Koch HM, Gonzalez-Reche LM, Angerer J. On-line clean-up by multidimensional liquid chromatography-electrospray ionization tandem mass spectrometry for high throughput quantification of primary and secondary phthalate metabolites in human urine. *J Chromatogr B Analyt Technol Biomed Life Sci* 2003; **784**: 169–182.

15 Koch HM, Christensen KLY, Harth V, Lorber M, Brüning T. Di-n-butyl phthalate (DnBP) and diisobutyl phthalate (DiBP) metabolism in a human volunteer after single oral doses. *Arch Toxicol* 2012; **86**: 1829–1839.

16 Koch HM, Becker K, Wittassek M, Seiwert M, Angerer J, Kolossa-Gehring M. Di-n-butylphthalate and butylbenzylphthalate - Urinary metabolite levels and estimated daily intakes: Pilot study for the German Environmental Survey on children. *J Expo Sci Environ Epidemiol* 2007; **17**: 378–387.

17 Koch HM, Lorber M, Christensen KLY, Pälmke C, Koslitz S, Brüning T. Identifying sources of phthalate exposure with human biomonitoring: Results of a 48h fasting study with urine collection and personal activity patterns. *Int J Hyg Environ Health* 2013; **216**: 672–681.

18 USEPA. Exposure Factors Handbook: 2011 Edition. US Environmental Protection Agency: Washington D.C, 2011.

19 Janjua NR, Frederiksen H, Skakkebæk NE, Wulf HC, Andersson A-M. Urinary excretion of phthalates and paraben after repeated whole-body topical application in humans. *Int J Androl* 2008; **31**: 118–129.

20 Moya J, Howard-Reed C, Corsi RL. Volatilization of chemicals from tap water to indoor air from contaminated water used for showering. *Environ Sci Technol* 1999; **33**: 2321–2327.

21 Moore CA, Wilkinson SC, Blain PG, Dunn M, Aust GA, Williams FM. Use of a human skin in vitro model to investigate the influence of 'every-day' clothing and skin surface decontamination on the percutaneous penetration of organophosphates. *Toxicol Lett* 2014; **229**: 257–264.

22 Gurunathan S, Robson M, Freeman N, Buckley B, Roy A, Meyer R *et al.* Accumulation of chlorpyrifos on residential surfaces and toys accessible to children. *Environ Health Perspect* 1998; **106**: 9–16.

23 Morrison GC, Shakila N, Parker K. Accumulation of gas-phase methamphetamine on clothing , toy fabrics and skin oil. *Indoor Air* 2014; **doi: 10.1111/ina.12159**.

24 Fetter CW. *Contaminant Hydrogeology*. MacMillan Publishing Company: New York, 1993.

25 Mavruz S, Ogulata RT. Investigation of air permeability of single jersey fabrics with different relaxation states. *J Text Inst* 2011; **102**: 57–64.

26 Ogulata RT, Mavruz S. Investigation of porosity and air permeability values of plain knitted fabrics. *Fibres Text East Eur* 2010; **82**: 71–75.

27 Gibson WB, Keller PR, Foltz DJ, Harvey GJ. Diethylene glycol mono butyl ether concentrations in room air from application of cleaner formulations to hard surfaces. *J Expo Anal Environ Epidemiol* 1991; **1**: 369–383.

28 Ghaddar N, Ghali K, Harathani J, Jaroudi E. Ventilation rates of micro-climate air annulus of the clothing-skin system under periodic motion. *Int J Heat Mass Transf* 2005; **48**: 3151–3166.

29 Lyman W, Reehl W, Rosenblatt D. *Handbook of Chemical Property Estimation Methods*. Ameican Chemical Society, 1990.

30 Weschler CJ, Salthammer T, Fromme H. Partitioning of phthalates among the gas phase, airborne particles and settled dust in indoor environments. *Atmos Environ* 2008; **42**: 1449–1460.

31 Noble RE. Environmental tobacco smoke uptake by clothing fabrics. *Sci Total Environ* 2000; **262**: 1–3.

32 Chien Y-C, Chang C-P, Liu Z-Z. Volatile organics off-gassed among tobacco-exposed clothing fabrics. *J Hazard Mater* 2011; **193**: 139–148.

33 Ueta I, Saito Y, Teraoka K, Miura T, Jinno K. Determination of volatile organic compounds for a systematic evaluation of third-hand smoking. *Anal Sci* 2010; **26**: 569–574.

34 Tichenor BA, Sparks LE, Jackson MD, Guo Z, Mason Plunket MACM, Rasor SA. Emissions of perchloroethylene from dry cleaned fabrics. *Atmospheric Environ - Part Gen Top* 1990; **24 A**: 1219–1229.

35 Chao CYH, Tung TCW, Niu JL, Pang SW, Lee RYM. Indoor perchloroethylene accumulation from dry cleaned clothing on residential premises. *Build Environ* 1998; **34**: 319–328.

36 Thomas KW, Pellizzari ED, Perritt RL, Nelson WC. Effect of dry-cleaned clothes on tetrachloroethylene levels in indoor air, personal air, and breath for residents of several New Jersey homes. *J Expo Anal Environ Epidemiol* 1991; **1**: 475–490.

526 37 Sherlach KS, Gorka AP, Dantzler A, Roepe PD. Quantification of perchloroethylene
527 residues in dry-cleaned fabrics. *Environ Toxicol Chem* 2011; **30**: 2481–2487.

528 38 Guerrero PA, Corsi RL. Emissions of p-dichlorobenzene and naphthalene from
529 consumer products. *J Air Waste Manag Assoc* 2012; **62**: 1075–1084.

530 39 Schreuder-Gibson H, Truong Q, Walker J, Owens J, Wander J, Jones W. Chemical and
531 Biological Protection and Detection in Fabrics for Protective Clothing. *MRS Bull* 2003;
532 **28**: 574–578.

533 40 Piadé JJ, D'Andrés S, Sanders EB. Sorption phenomena of nicotine and ethenylpyridine
534 vapors on different materials in a test chamber. *Environ Sci Technol* 1999; **33**: 2046–
535 2052.

536

Table legend

Table 1. Net amount of metabolites excreted during the time period from entering the chamber until 54 hours later, as well as parent compound uptake calculated from the metabolite levels; details regarding the calculation of the listed values are presented in Supporting Information.

Figure legends.

Figure 1. Normalized mass of DEP and DnBP absorbed for fresh and exposed clothes experiments. Also shown for comparison are results from the 6 bare-skinned participants (boxplot) reported in Weschler et al.[8] The line within the box represents the median; the bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.

Figure 2. Net amount of MEP (2a) and MnBP (2b) excreted from beginning of exposure until last urine sample. Results for fresh and exposed clothes are compared against the bare skin results of the closest aged participant in Weschler et al.[8]

Figure 3. Normalized dermal uptake of DEP and DnBP versus age. Shown are results from this research (clothes) and results for six bare skin participants reported by Weschler et al.[8]

Figure 4. Normalized metabolite excretion rate for MEP and MnBP. Shown are results from this research (clothes) and results for six bare-skinned participants reported by Weschler et al.[8] The line within the box represents the median; the bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.

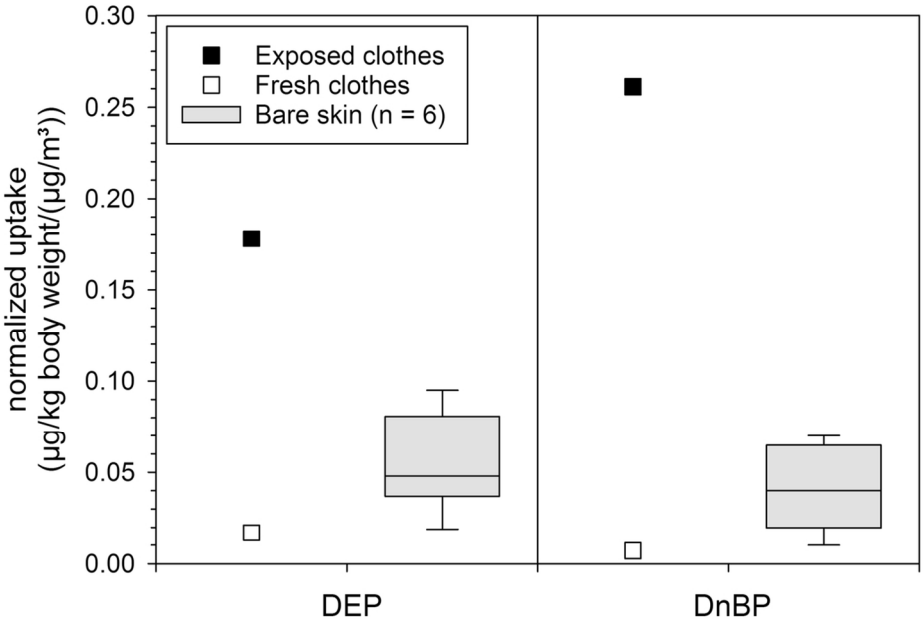

Figure 1. Normalized mass of DEP and DnBP absorbed for fresh and exposed clothes experiments. Also shown for comparison are results from the 6 bare-skinned subjects (boxplot) reported in Weschler et al.[8] The line within the box represents the median; the bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.
114x80mm (300 x 300 DPI)

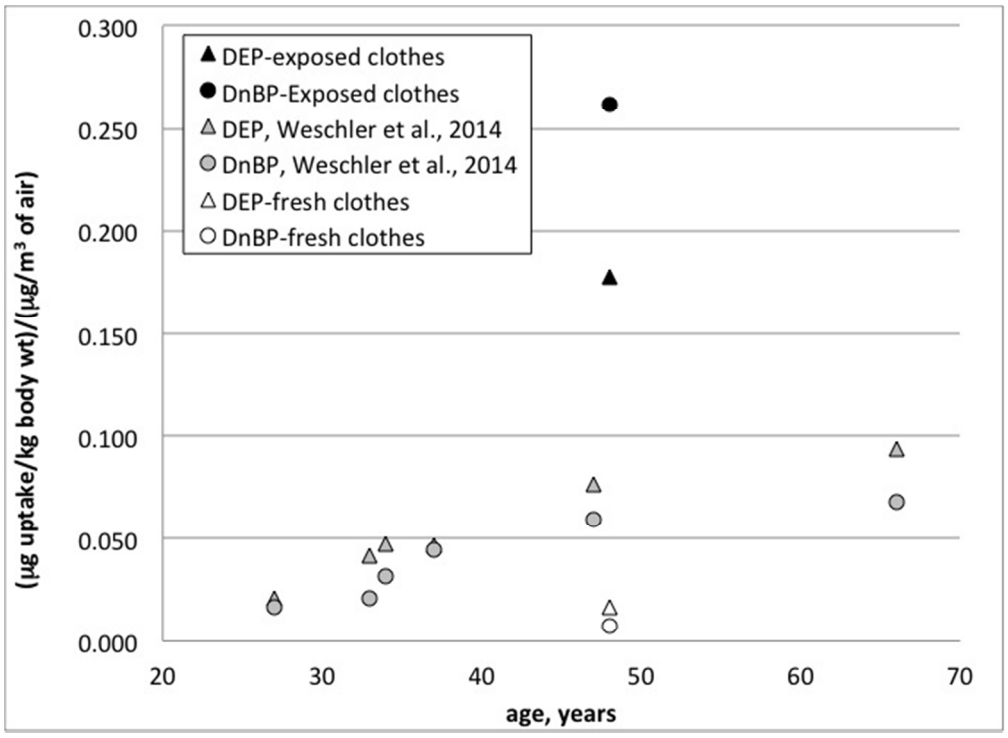

Figure 3. Normalized dermal uptake of DEP and DnBP versus age. Shown are results from this research (clothes) and results for six bare skin subjects reported by Weschler et al.[8]
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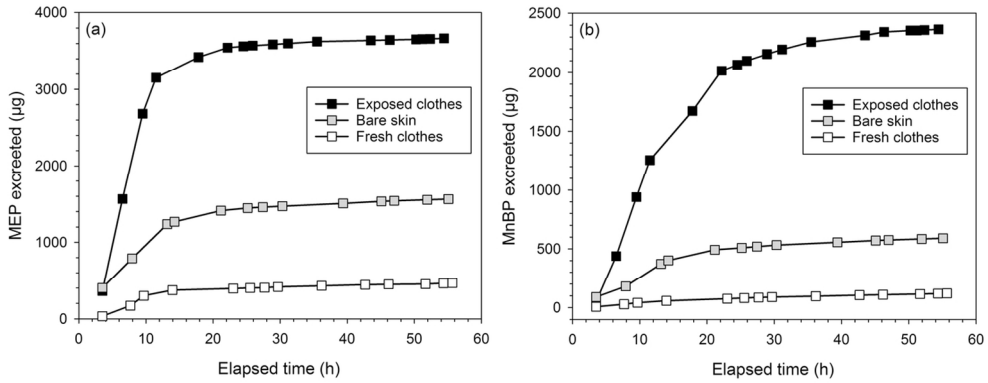

Figure 2. Net amount of MEP (2a) and MnBP (2b) excreted from beginning of exposure until last urine sample. Results for fresh and exposed clothes are compared against the bare skin results of the closest aged subject in Weschler et al.[8]
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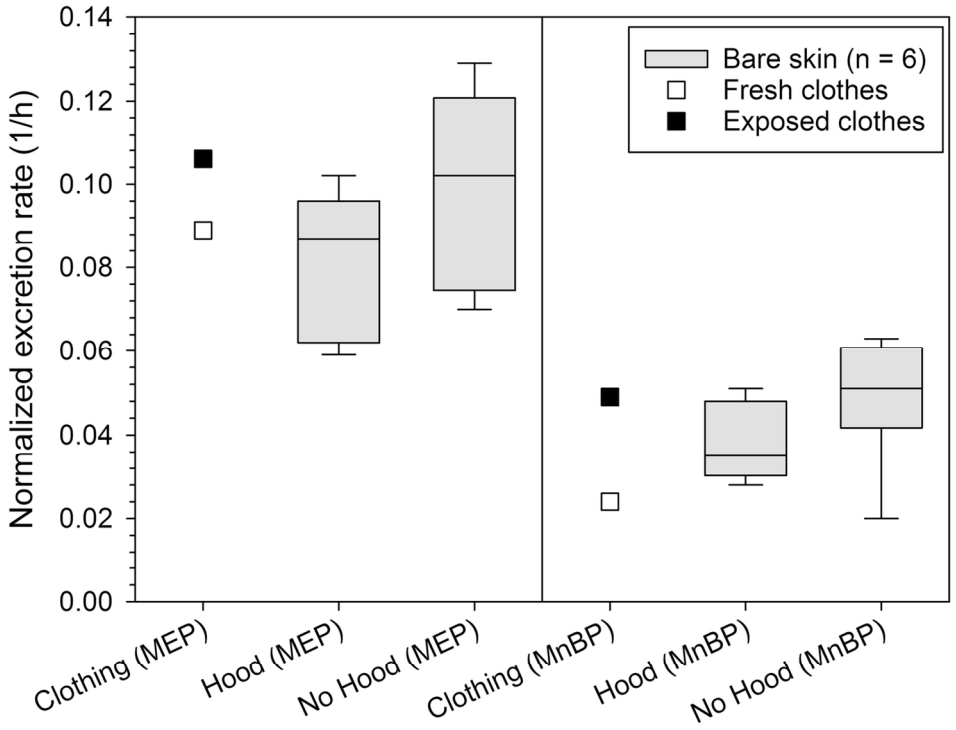

Normalized metabolite excretion rate for MEP and MnBP. Shown are results from this research (clothes) and results for six bare-skinned subjects reported by Weschler et al.[8] The line within the box represents the median; the bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.
129x108mm (300 x 300 DPI)

Table 1. Net amount of metabolites excreted during the time period from entering the chamber until 54 hours later, as well as parent compound uptake calculated from the metabolite levels; details regarding the calculation of the listed values are presented in Supporting Information.

	Metabolites excreted (µg)			Total uptake parent (µg)		Background corrected uptake parent (µg)		Dermal only uptake parent (corrected for concentration in hood) (µg)		Normalized dermal uptake (µg/kg/(µg/m^3)		Average flux based on 6 hour exposure (µg /m^2/h)	
	MEP	MnBP	3OH-MnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP
Fresh clothing	466	121	7.7	634	176	522	98	352	74	0.017	0.007	28	6
Exposed clothing	3666	2367	136	4995	3432	4882	3355	4712	3331	0.178	0.261	381	270

Supplemental Material

Role of clothing in both increasing and decreasing dermal absorption of airborne SVOCs

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Table of Contents for Supplementary Materials

Table S1. Clothing characteristics determined from product packaging or labels

Clothing	Composition	Size	Manufacturer	Description
Undershirt	100% cotton	M/M, 38-40" (97-102 cm)	Gildan	Short sleeve, crew neck, color: white Estimated cloth area = 0.91 m^2
Underwear	100% cotton with elastic band	L/G, 36-38" (91-97 cm)	Hanes	Boxer style briefs, color: grey Estimated cloth area = 0.24 m^3
Shirt	100% cotton	M	Gildan	Long sleeve tee-shirt, crew neck, color: dark green Estimated cloth area = 1.03 m^3
Pants	100% cotton	36" (91 cm) waist 36" (91 cm) inseam	Wrangler	Jeans, slim fit, color: dark blue Estimated cloth area = 1.10 m^2
Socks	85% cotton 12% polyester 1% elastic 1% nylon 1% spandex	12W-15	Starter	Tube socks that rise ~20 cm above ankle, color: white Estimated cloth area (pair) = 0.07 m^2

Figure S1. Male subject shown wearing full set of test clothing and the breathing hood while seated in the test chamber.

Table S2. Net amount of metabolites excreted during the time period from entering the chamber until 54 hours later, as well as parent compound uptake calculated from the metabolite levels. This Table is identical to Table 1, but is included here with detailed explanations of calculation methods.

	Metabolites excreted (µg)[1]			Total uptake parent (µg)[2]		Background corrected uptake parent (µg)[3]		Dermal only uptake parent (corrected for concentration in hood) (µg)[4]		Normalized dermal uptake (µg/kg/(µg/m^3)[5]		Average flux (µg /m^2/h)[6]	
	MEP	MnBP	3OH-MnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP
Fresh clothing	466	121	7.7	634	176	522	98	352	74	0.017	0.007	28	6
Exposed clothing	3666	2367	136	4995	3432	4882	3355	4712	3331	0.178	0.261	381	270

1. The mass of metabolites excreted is determined by multiplying the concentration of each metabolite by the volume of urine collected for each sample and summing over all samples collected during the 54 hour period after the exposure started.

2. Total parent uptake is calculated by converting mass from metabolite to parent and using a metabolic conversion factor.

Compound	Abbreviation	CAS-no.	Molecular weight (g/mol)	Metabolic conversion factor
Diethylphthalate	DEP	84-66-2	222.24	NA
Di-n-butylphthalate	DnBP	84-74-2	278.34	NA
Monoethylphthalate	MEP	2306-33-4	194.18	0.84
Mono-n-butylphthalate	MnBP	131-70-4	222.24	0.84
3OH-mono-n-butylphthalate	3OH-MnBP	57074-43-8	238.24	0.07

DEP = [(MEP /194.18) * 222.24]/0.84
DnBP = [(MnBP /222.24)* 278.34]+ [(3OH-MnBP /238.24) * 278.34] / (0.84+0.07)

3. Background-corrected uptake of the parent compound is determined by subtracting out the background concentration of metabolites, integrating the resulting mass, then applying the conversion described in (2) above. Background is defined as the pre-exposure urine concentration.

4. Dermal uptake of parent compounds is calculated by subtracting from background-corrected uptake the inhaled mass of DEP and DnBP based on concentrations in breathing air of the hood (40.7 and 5.7 µg/m^3, respectively). Inhalation rate is assumed to be 0.7 m^3/h. Therefore, the mass subtracted is 170 and 24 µg for DEP and DnBP respectively.

5. Normalized uptake is calculated by dividing the dermal uptake by average exposure air concentration and the subject body mass. Average air concentrations during the fresh clothing experiment were 230 µg/m^3 DEP and 113

μg/m^3 DnBP. Average air concentrations during the exposed clothing experiment were 291 μg/m^3 DEP and 140 μg/m^3 DnBP.

6. The average flux is estimated from the "Dermal only" corrected parent compound uptake, divided by exposed surface area of the participant and the exposure period (6 hours). Exposed surface area is taken as 2.06 m^2, estimated by equation 7A-7 of the Exposure Factors Handbook[18] and corrected for the area of the head (6.6% of total).